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THE MARSHALL SPACE FLIGHT CENTER LOW-ENERGY ION FACILITY – A PRELIMINARY REPORT

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16. ABSTRACT

The Low-Energy Ion Facility (LEIF) is designed for laboratory research of low-energy ion beams similar to those present in the magnetosphere. In addition, it provides the ability to develop and calibrate low-energy, less than 50 eV, plasma instrumentation over its full range of energy, mass, flux, and arrival angle. This report describes the current status of this evolving resource. It also provides necessary information to allow users to utilize it most efficiently.

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ACKNOWLEDGMENTS

The system described here has evolved through several projects, and has benefited from the valuable contributions from many people. While in no way inclusive, the authors wish to make note of several of these contributions. The original ion source was provided by Dr. Nobie Stone. The source was additionally developed by Dr. David Reasoner for calibration of the Light Ion Mass Spectrometer (LIMS) for flight on the DOD/NASA Satellite Charging at High Altitude (SCATHA) spacecraft, and by Mr. Stanley Fields for calibration of the Retarding Ion Mass Spectrometer (RIMS) instrument for the Dynamics Explorer-1 spacecraft. Mr. Richard Hamilton provided indispensable laboratory support. Dr. Charles R. Chappell provided overall program guidance.

TECHNICAL MEMORANDUM

THE MARSHALL SPACE FLIGHT CENTER LOW-ENERGY ION FACILITY – A PRELIMINARY REPORT

INTRODUCTION

The earliest low-energy, less than 100 eV, charged particle detectors were designed to measure the temperature and total density of a plasma which was initially assumed to consist of drifting, thermal, ionized hydrogen and helium. The instrument acceptance angles tended to be nearly hemispherical in extent and relied on the spacecraft spin for directional resolution. This early picture became more complicated by the discovery of the magnetosphere for such phenomena as ions of oxygen and nitrogen, and anisotropic field-aligned ion flows with drift velocities of 25 km/s and more. The realization that the ionospheric plasma was transported into the magnetosphere brought about the development of a new class of instrumentation that is differential in mass, energy, and direction. Each enhancement in performance has in turn revealed a whole new set of phenomena and has raised questions which require additional instrumental resolution in order to answer. The resulting next generation of instruments, some with prototypes already being evaluated, is able to resolve the imperfections in the laboratory sources used to calibrate them.

The Marshall Space Flight Center Space Science Laboratory Low-Energy Ion Facility (LEIF) has been established for laboratory research and to develop and experimentally calibrate the response of low-energy charged particle detectors over their complete range of particle energy, mass, flux, and angular acceptance. The facility includes an environmental vacuum chamber, a test article fixture, an ion source, and supporting electronics and instrumentation for the various components. The purpose of this document is to describe the facility, document the range of the various performance parameters, and in general provide the necessary information to enable users to best utilize the facility.

VACUUM SYSTEM

The chamber is used to develop and calibrate flight instrumentation which have detectors such as channel electron multipliers [1] that are easily contaminated by hydrocarbons. It is absolutely necessary to insure that no contamination is introduced by the chamber and pumping facilities. To preclude this, the chamber is evacuated sequentially by four different types of pumps. The pumps shown in Figure 1 are the rotary carbon vane pump (A), the liquid nitrogen cooled sorption pump (B), the liquid helium cryogenic pump (C), and the ion pumps (D). A small liquid nitrogen shroud 70 cm in diameter and 30 cm long is located in the rear of the chamber (E). Figure 2 shows a typical chamber pumpdown cycle. The base chamber pressure is approximately 1×10^{-8} Torr. However, normal operation of the ion source raises the chamber pressure to the high 10^{-7} Torr range due to the throughput of the working gas. The exact pressure depends on the background pressure of the chamber, the working gas in use, and the flux required from the source.

Dry, pure gaseous nitrogen derived from boiling liquid nitrogen is used for backfilling of the chamber to ambient pressure. The vacuum chamber is bakeable to a temperature of 250°C to provide a clean environment for the experimental research and calibration of flight instruments. The pressure is monitored by thermocouple, ion gauges, and the pressure function of the ion pumps at the appropriate ranges of the pumpdown. The time required to reach high vacuum is determined by the size of the test article, its outgassing rate, and the time the system has been at ambient conditions. Pumpdown of an instrument that has been properly cleaned and outgassed usually requires 2 days to reach within a factor of 2 of the ultimate chamber pressure. In practice, there are usually sufficient voids and virtual leaks in the instrument under test that it will hold the chamber in the low 10^{-7} Torr range for several days. This is usually acceptable in view of the low ion energies involved which preclude secondary impact ionization.

The vacuum chamber is 122 cm in diameter and 183 cm long. Access to the chamber is by a 122 cm diameter door mounted on a roll-away dolly for test article installation. Thus, there are no constraints on access to the instrument for final connection and operation of any moving components during installation. The chamber has access ports of the nominal size 2-3/4 in. and 6 in. O.D. on the sides and top of the vacuum chamber. The ports are available for support of the operation of the experimental package. The feedthrough ports are for electrical, liquid, gas, visual, and mechanical access. Virtually any configuration of feedthroughs can be accommodated:

Electrical: The feedthroughs that are available can accommodate power up to 10 kV and 50 A. Others are for instrumentation and thermocouples.

Liquid: The liquid feedthroughs are the dual type with a flow rate of a few gallons per minute.

Gas: Gas feedthroughs may be added to support the requirements of the instrument package.

Mechanical: The mechanical feedthroughs are limited to the positive drive and magnetic rotary ball bearing types.

The test hardware may be viewed by non-optical quality glass view ports. Lighting under ambient and vacuum conditions is also provided to view the hardware. The interior of the vacuum chamber operates normally at or slightly above the ambient room temperature, usually 15 to 20°C. No active thermal controls are available. Quartz lamps can be mounted to provide heating of the test article if desired.

The test article is partially protected from the ion pumps by a solid line-of-sight baffle installed in the rear of the chamber. Additionally, the pump throats are covered by fine mesh grounded screens. These substantially reduce the spurious pickup to high impedance detectors due to escaping high energy electrons, background gas ionization, and capacitively coupled noise. For proper testing, the instrument must have full normal electrical shielding in place. The requirement for effective electrical shielding is more stringent than for diffusion or turbomolecular pumped systems.

TEST ARTICLE FIXTURE

The test article is mounted in the vacuum chamber in a rigid "A" frame design (Fig. 3). Instruments are normally mounted with the detector aperture flush with the fixture top in the axes of rotation and tilt. This round table is 61 cm in diameter, grounded to the chamber electrical ground, and shields

the remainder of the instrument from the ion beam. The table can be rotated ±180 deg about the vertical axis, and tilted ±90 deg about the horizontal axis. The tilt axis is controlled by a stepping motor which allows the angles to be chosen and reset in increments of approximately 10 min. The rotation axis can be set to approximately 30 min of arc. The total extent of the package, including support fixtures, must be less than 35 cm below the tilt table top in order to clear the chamber floor. A maximum moment arm of 15 kg-m can be accommodated. Devices not requiring rotation under vacuum can be somewhat larger and more massive. The chamber cycle time must be kept firmly in mind, however.

ION SOURCE

The ion source (Fig. 4) is a Kaufman thruster [2-3] modified to allow operation in the low density and ion energy regimes necessary for space environment simulation. The primary modification is in the electron impact ionizer system used to produce a source of ions. Unlike the traditional Kaufman thruster, the source of electrons is placed outside rather than inside the large mesh screen chamber which serves as the anode. The anode bias sets the beam energy with respect to the chamber ground. This anode forms an equipotential cavity in which all the source ions are formed. The parallel energy distribution on the extracted beam is considerably reduced since all the ions are born in a constant potential region. This is in contrast to the normal case in which the voltage gradient between the anode and cathode, typically on the order of 100 V, lies entirely within the ionization chamber. Of course, the full drop doesn't appear as thermal spread on the beam for several reasons. The mean free path for particles is usually short, approximately 10 percent of the ionization chamber length. Also, charged particles impact the chamber wall where they can thermalize [4]. Nevertheless, some vestiges of the large voltage drop do pass through to the beam. For the source configuration used, the energy spread is much narrower than Maxwellian at energies above 10 eV, and gradually becomes quasi-Maxwellian below that level. The 0.2 to 0.3 eV temperature spread is typical of such discharges, and represents a nearly irreducible minimum (Figs. 5 and 6). Table 1 shows typical source parameters.

The source is 9 cm in diameter with 97 small diameter "beamlets" to provide a uniform, parallel coverage of the instrument aperture. It is constructed primarily of stainless steel and ceramics to insure maximum purity of the beam. Tungsten wire is used for both the ionizer and neutralizer wires. The latter is needed to control beam blowup due to space charge. It also allows fine adjustment of the beam space charge potential. The electron distribution consists of two distinct populations. The first, about 90 percent of the total population, is less than 5 eV and is produced by the neutralizer. The remaining 10 percent may be as energetic as 100 eV and consists of the few which pass through the ionization chamber without suffering any inelastic collisions. The high energy population can be reduced somewhat by reducing the bias potential of the ionizer so that it is below the extractor grid potential. This does reduce the output and increases the neutral gas throughput, however.

Because the source must produce ions of less than 1 eV of energy, perturbing electric and magnetic fields must be kept to a minimum. The neutralizer wires, consisting of 0.0254 cm (0.01 in.) tungsten, typically generate large magnetic fields from the current and electric fields from the voltage drop across their surface. The neutralizer wires (Fig. 4) are bent into a hairpin shape to largely cancel the electric and magnetic fields which they generate. These could otherwise deflect the beam at low energies.

Figures 7 and 8, and Figures 9 and 10, show typical results without and with beam neutralization, respectively. These figures were obtained by using a contouring program which processed the discrete measurements obtained with a retarding potential analyzer on a two-axis translator table. Unneutralized, the beam spreads rapidly under space charge effects. The irradiation is nearly uniform with the spot size consistent with the last aperture in the drift tube. By comparison, the fully neutralized beam is spread

very little. Some tradeoffs can be made in beam uniformity versus divergence. The deflection from center is due to the terrestrial magnetic field. The chamber geometry, lack of defocusing perturbing electric or magnetic fields, and careful neutralization of the beam insure that the beam arrives at the instrument aperture essentially parallel when properly neutralized. The beam spot size has been measured to be only slightly larger than the source aperture. Below approximately 25 eV, the ambient magnetic field induces a slight deviation from normal incidence which is noticeable. This has the effect of changing the effective normal incidence to the instrument under test and can easily be corrected in the data analysis. The degree of collimation, and the resulting uniformity of the arriving current density, changes with beam current and particle energy. The least uniform current density obtained occurs at minimum energy for two reasons. First, the spread of the beam is not dominated by the beam optics, but by the superimposed energy spread of the ions which exists in the source discharge. Second, the terrestrial magnetic field deflects the beam sufficiently that structure from the edge of the source aperture begins to be noticeable. Under worst-case measured conditions, the beam current varies by less than 5 percent over a 1 cm radius instrument aperture.

The gas feed to the source is actively regulated by a neutral pressure controller which monitors the gas feedline to the ionization chamber. This makes the source output essentially independent of the background chamber pressure. The normal source filling pressure is approximately 40 m Torr. The source is thermally clamped to a large heat sink in order to dissipate the ohmic heating from the ionizer and the neutralizer filaments. These two precautions provide excellent stability in source output and energy once the operating temperature is reached. This process is accelerated by the use of quartz lamps. These lamps are usually used to keep the source at or near its normal operating temperature when the source is not in use.

The source is located in a drift tube mounted above the chamber (Fig. 11). A pneumatic valve allows this tube to be isolated from the rest of the system so that it is constantly under vacuum. This drift tube serves dual purposes. First, it allows the installation or modification of a test article without contaminating the source with ambient air. Second, it further reduces the beam divergence as seen at the test article. Supplementary heating insures that no moisture or other contaminants from the instrument under test will condense on the source when it is opened to the main chamber after the latter is cycled to atmosphere.

Dry LN_2, derived from boiling LN_2, is normally used to provide an N_2^+ beam for development purposes. Other gases may also be used. Final calibration is performed using special high purity bottled gas. A greater purity could be obtained by a beam refined by a velocity or momentum selector [5]. This purity is obtained at the cost of total throughput due to the slight parallel and perpendicular energy spreads on the beam, as well as the inevitable defocusing fringing fields. The problem is especially difficult below 5 eV. Since the relative abundance of each species may be measured concurrently with the test instrument throughput, the slight complication is a good tradeoff. Figure 12, obtained using an ion mass spectrometer [6], shows the relative purity of the beam. The main impurity is actually ionized atomic nitrogen. This is a result of the high electron energy, approximately 150 eV, needed to produce a high density plasma in the ionization chamber [7]. This condition is required to produce a high current, low divergence beam. If a divergent beam and lower particle output can be tolerated, the singly ionized molecular nitrogen component can be increased to 95 percent. The additional background impurities are from background contamination which would be baked out before actual chamber used. Additional gasses can be used to enhance the number of peaks for a particular test.

CHAMBER DIAGNOSTICS

A variety of instruments can be used to make precise determinations of the beam during calibration of an instrument. A retarding potential analyzer (RPA) (Fig. 3) is normally placed directly over the instrument aperture, and virtually coplanar with it, to determine unambiguously the beam energy, density, and energy spread. The beam purity will be monitored with an Ion Mass Spectrometer which continuously samples a portion of the source output. The unavoidable deviations in the source from a monoenergetic, single species beam can then be accurately calibrated out of the instrument response.

In addition to the facilities mentioned above, a two-axis translator is available which allows an RPA or other instrument to be placed accurately under the instrument. This allows, for example, the output distribution from a portion of an instrument to be mapped and then compared with the input response from the following instrument stage. This currently requires the instrument to be parallel to the chamber floor. A small RPA with a restricting cap to increase spatial resolution at the cost of decreased total current is used where possible to minimize the uncertainties introduced by more sophisticated detectors and amplifiers.

CONCLUSION

The current LEIF provides good facilities for developing and calibrating instruments in the energy range of 5 to 100 eV. The parameters which can be measured include mass, energy, and angular response. Further refinements to the system are being developed. These include magnetic shielding to reduce ambient fields, improved output from the ion source below 5 eV, and more sophisticated instrumentation and precision manipulation facilities. A microcomputer will soon be available to control both the source and the positioning of the test article. This will be able to interface with Ground Support Equipment over an RS-232-C link, if desired. The result will be a source which will generate a known, reliable beam with only routine operator intervention.

TABLE 1. TYPICAL SOURCE PARAMETERS

Beam Energy (eV)	ΔE/E (FWHM)	Density[a] (cm^{-3})	J/J_o[b]
50	0.0019	880	0.04
40	0.0019	1340	0.05
30	0.0032	920	0.06
20	0.0013	560	0.05
10	0.0500	245	0.03
7.4	0.0610	99	0.02
5.3	0.124	99	0.02
3.4	0.157	93	0.03

a. These densities can be reduced with usually some improvement in other beam parameters.

b. Ratio of difference in flux 1 cm from center of instrument aperture to the flux at the center.

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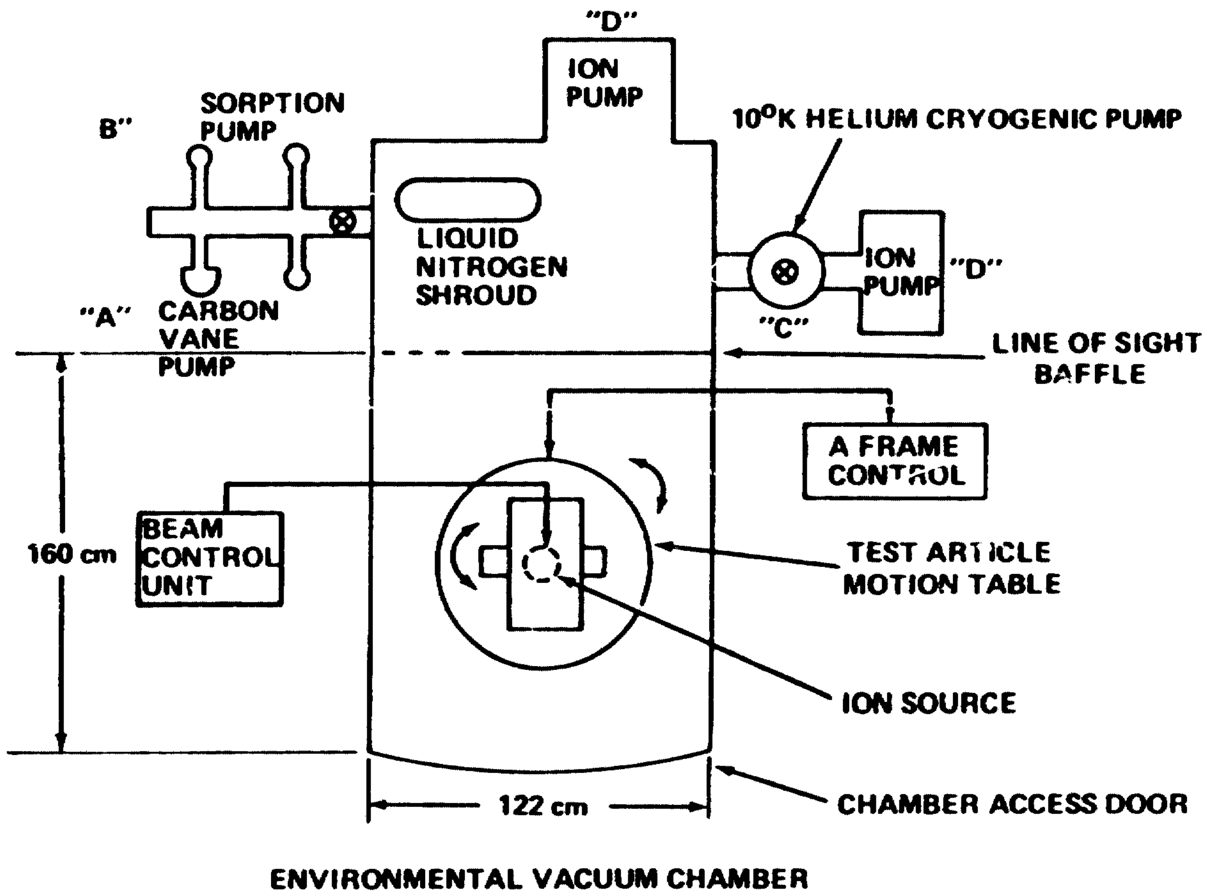

Figure 1. The LEIF facility uses a variety of oil-free pumps to insure minimum contamination.

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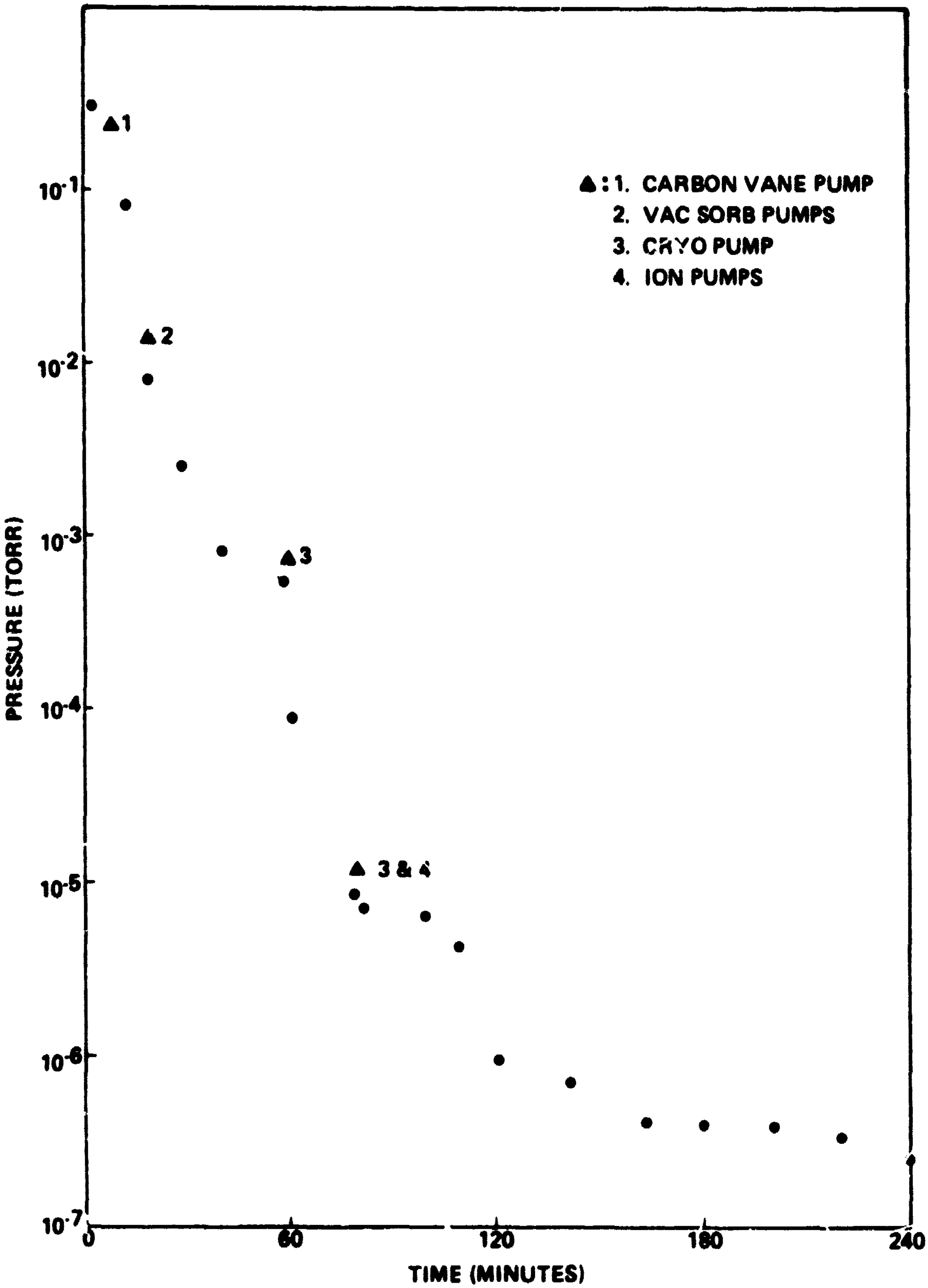

Figure 2. A typical chamber pumpdown sequence after installation of a clean test object.

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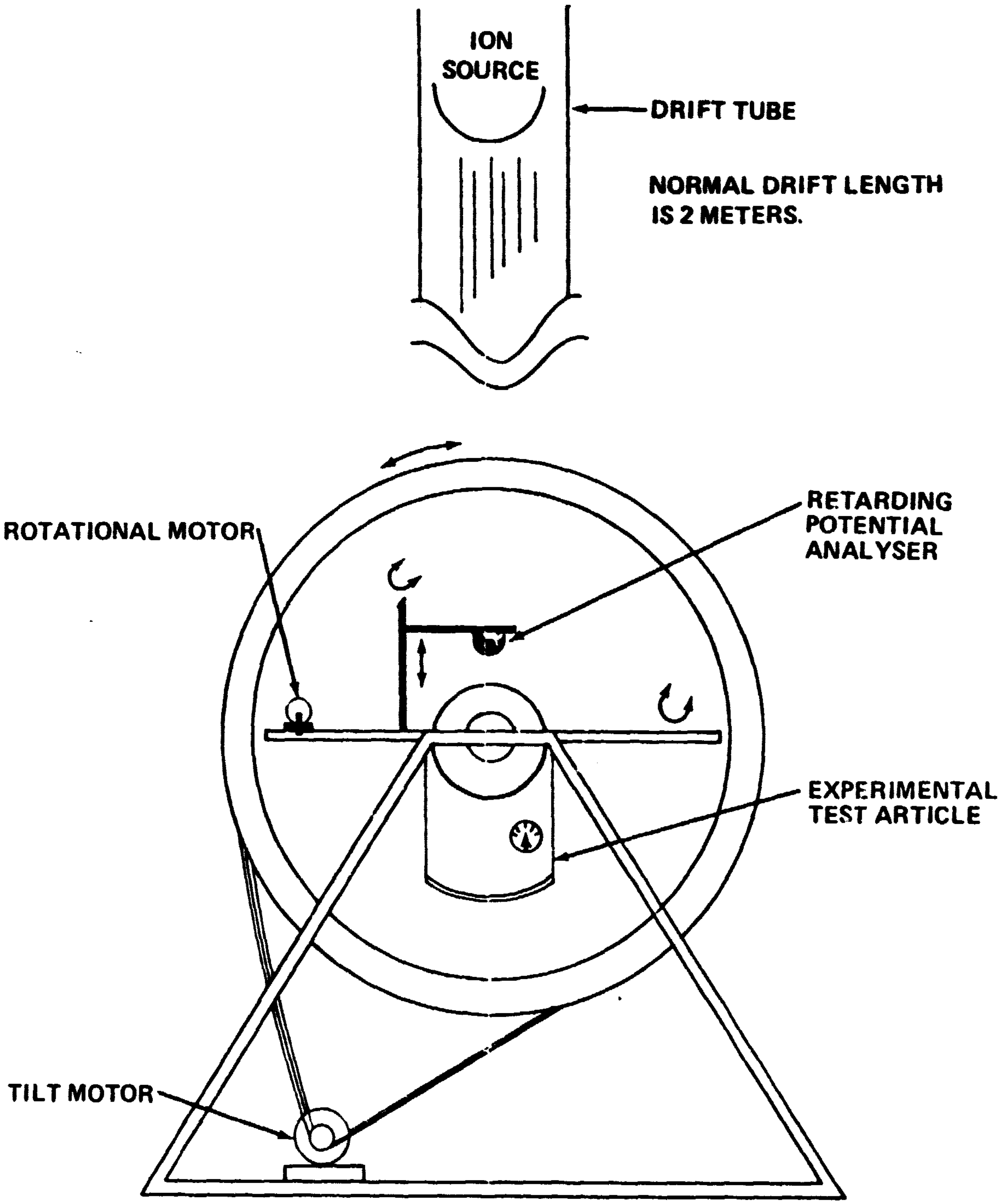

TEST ARTICLE MOTION TABLE

Figure 3. The test artic' fixture will rotate the article ±180 deg, and will simultaneously tilt the article ±90 deg. A reference Retarding Potential Analyzer (RPA) can be placed directly over the test article aperture for exact calibration.

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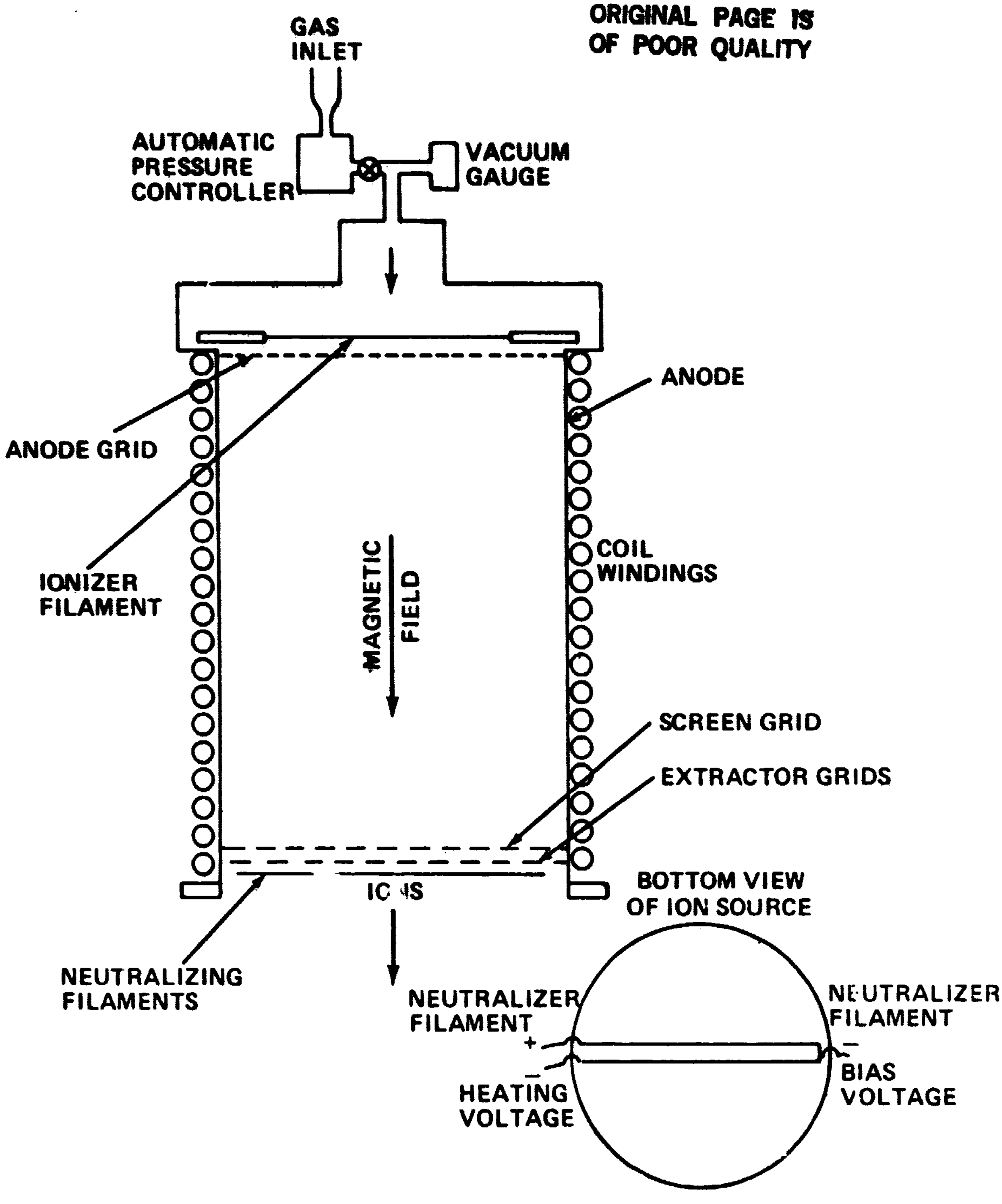

Figure 4. Sketch of LEIF ion source.

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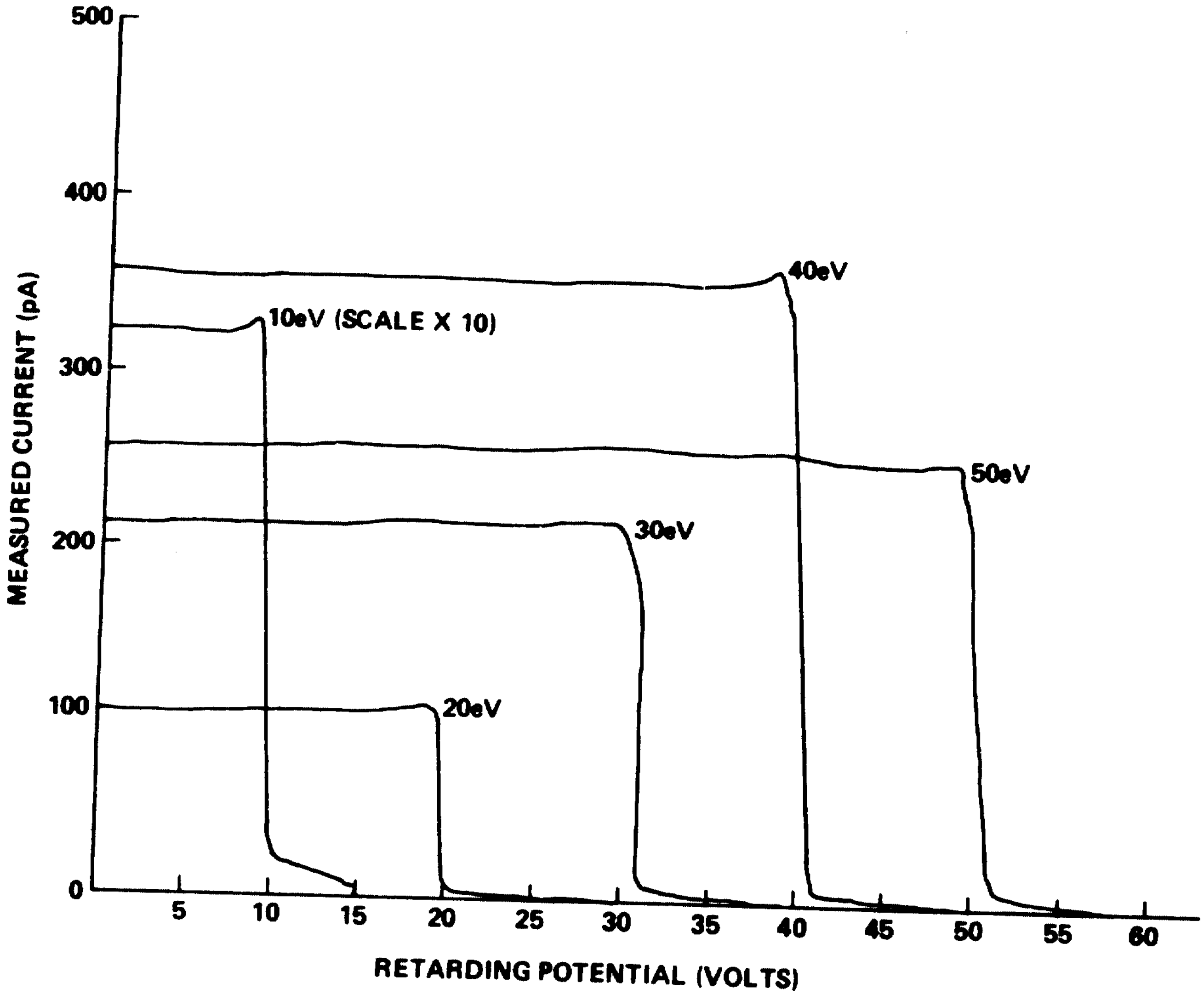

Figure 5. Retarding Potential Analyzer curves in the 10 to 50 eV range.

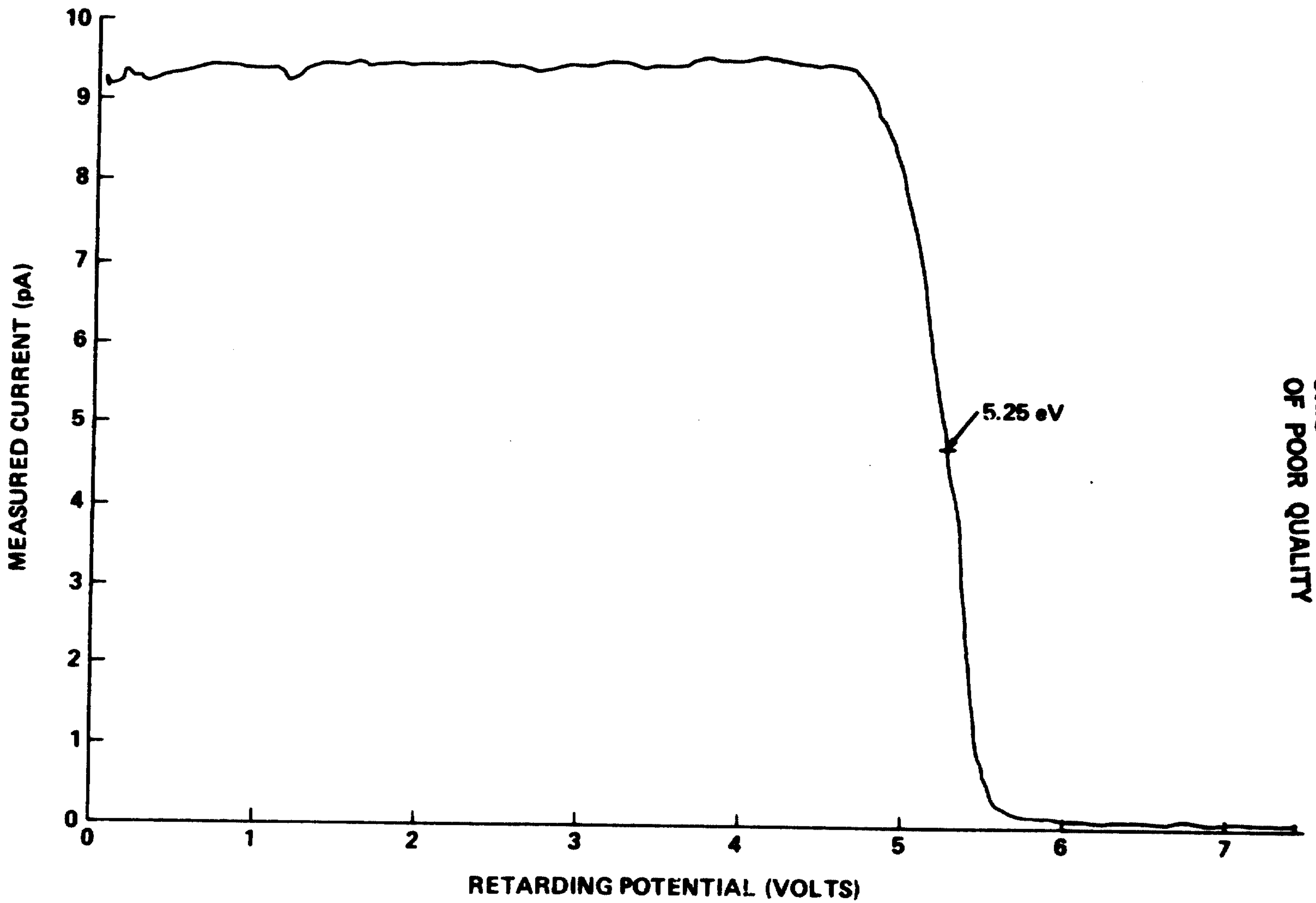

Figure 6. Retarding Potential Analyzer curve at 5 eV.

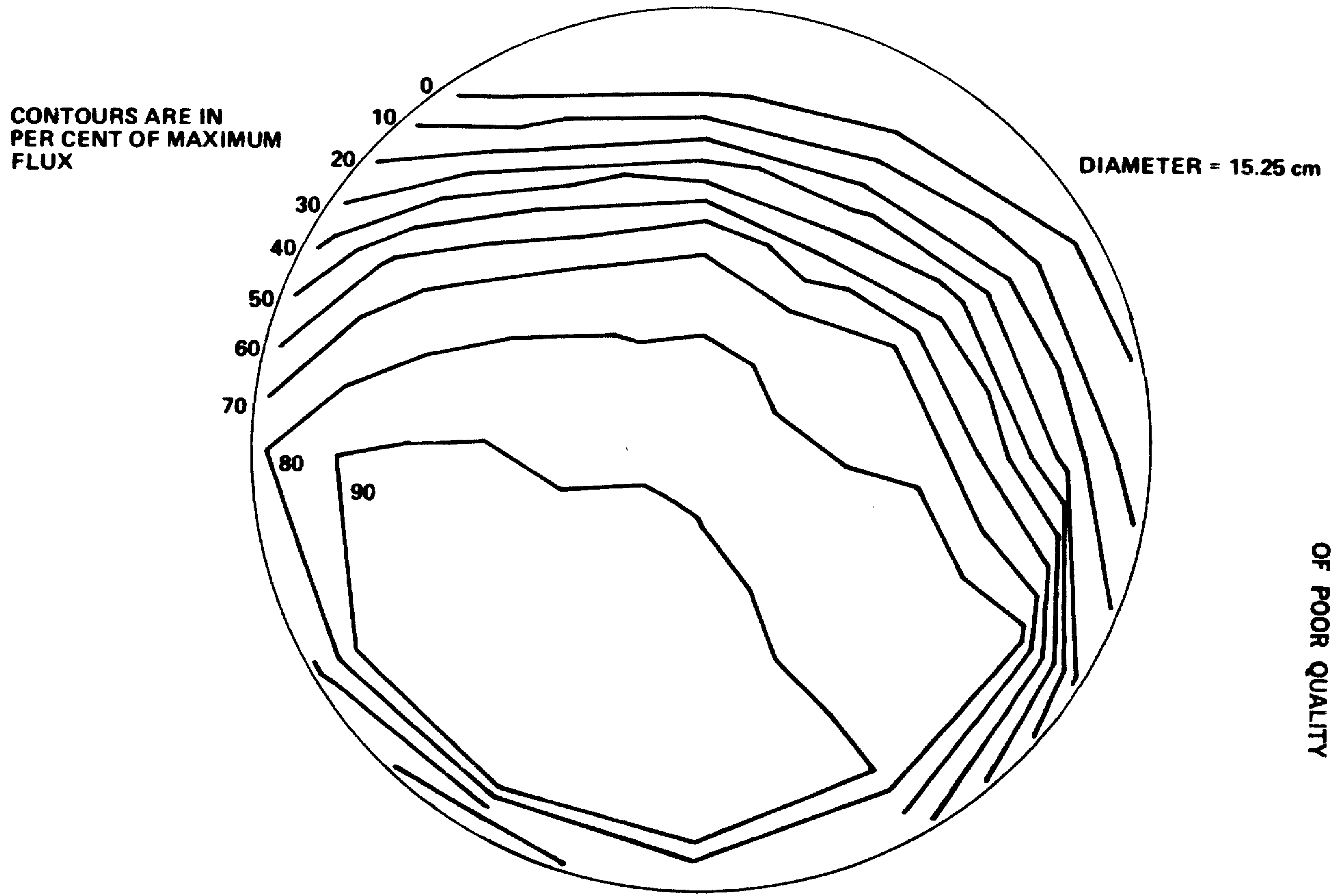

Figure 7. Contours oi equal intensity of flux at 25 eV using N_2^+ without neutralization.

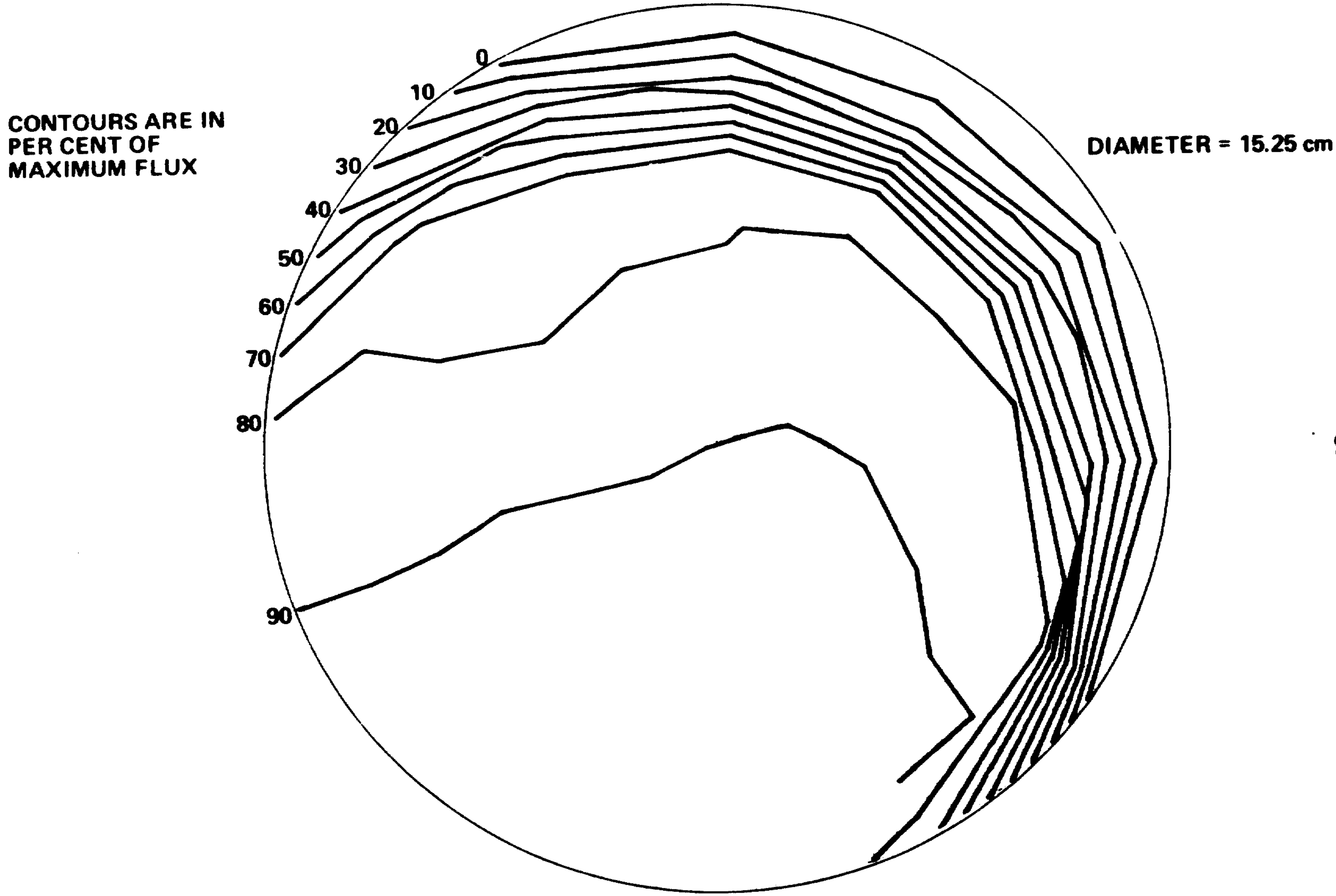

Figure 8. Contours of equal intensity of flux at 35 eV using N_2^+, without neutralization.

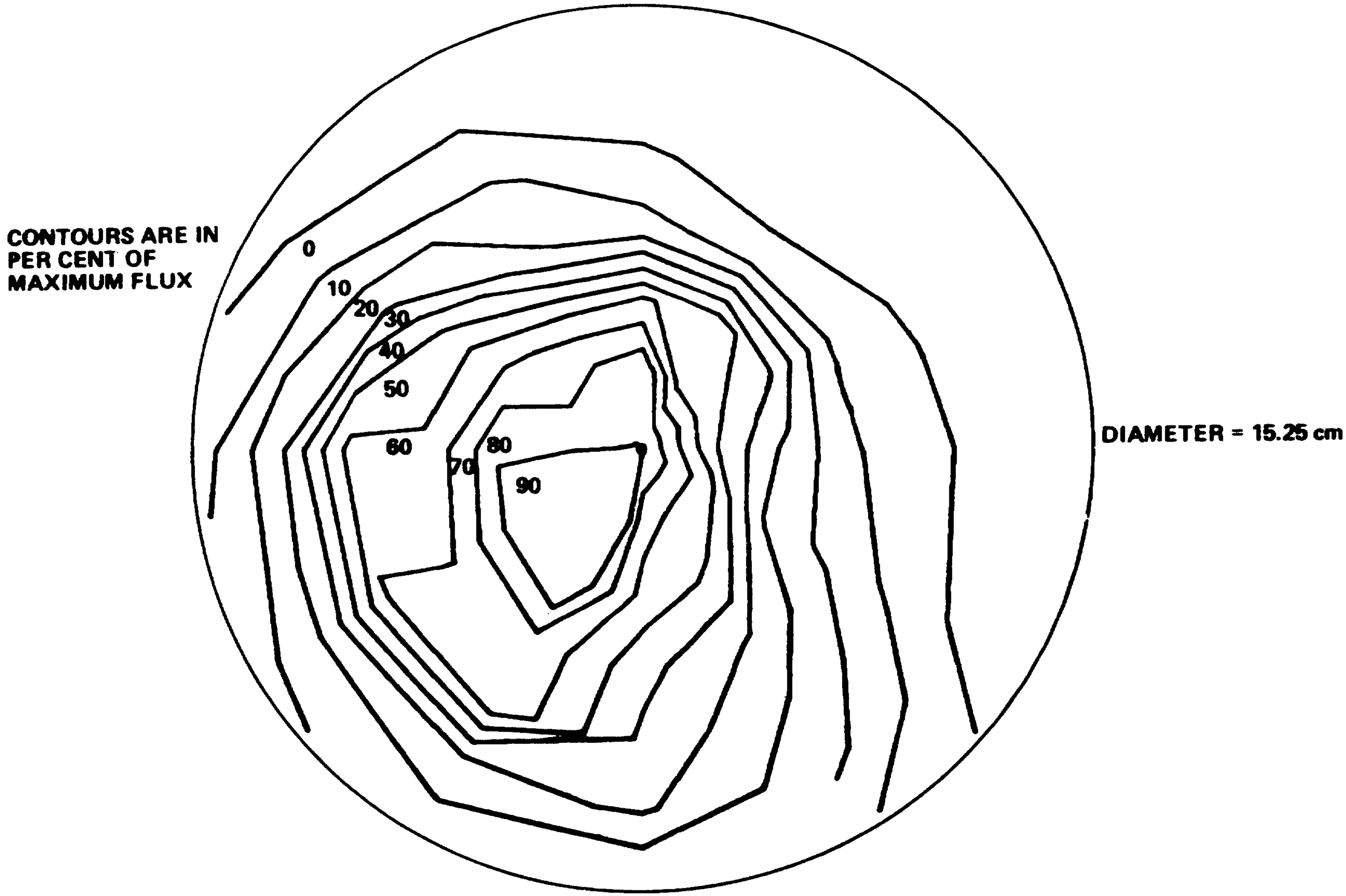

Figure 9. Contours of equal intensity of flux at 25 eV using N_2^+, with neutralization.

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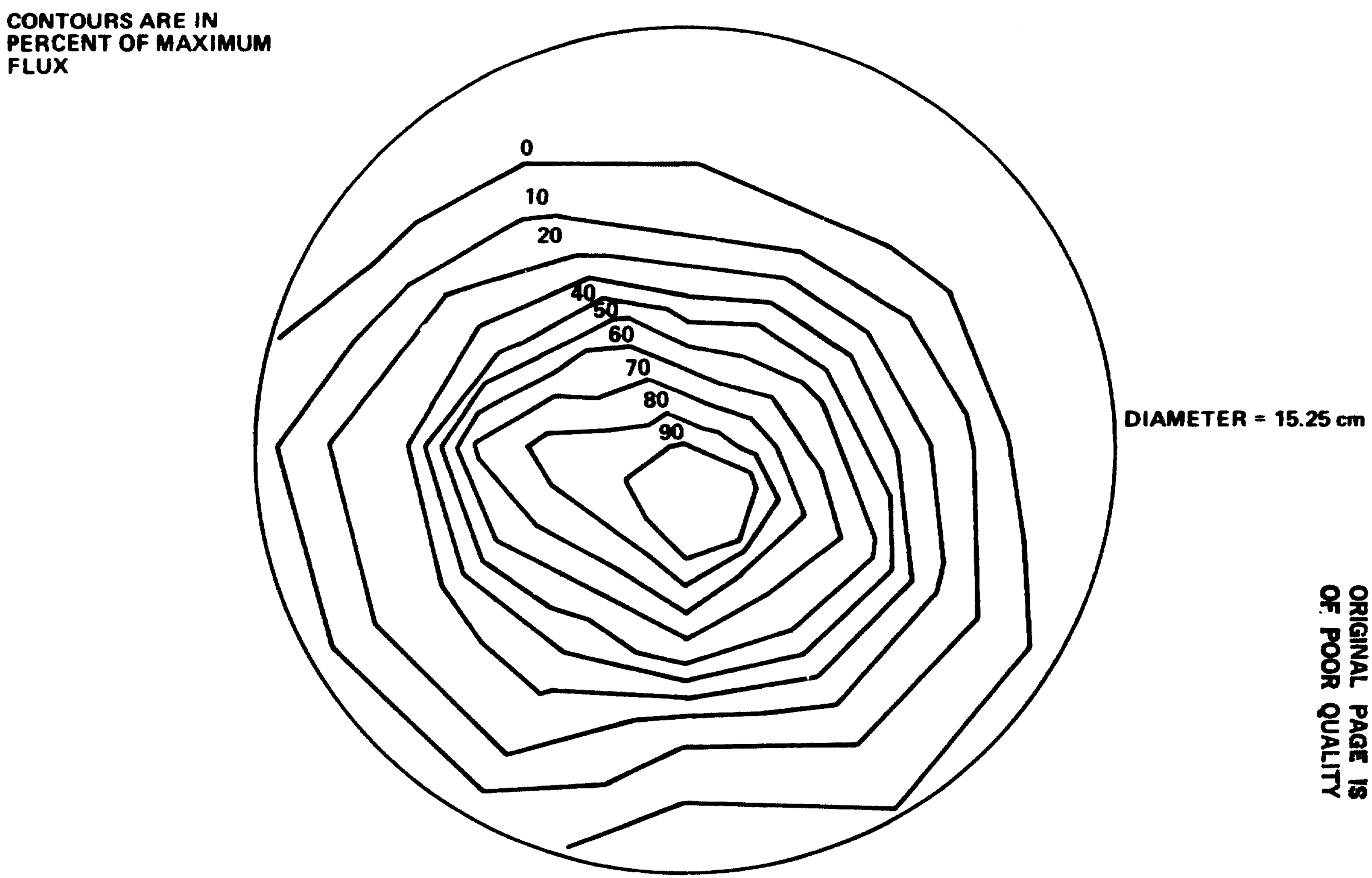

Figure 10. Contours of equal intensity of flux at 35 eV using N_2^+, with neutralization.

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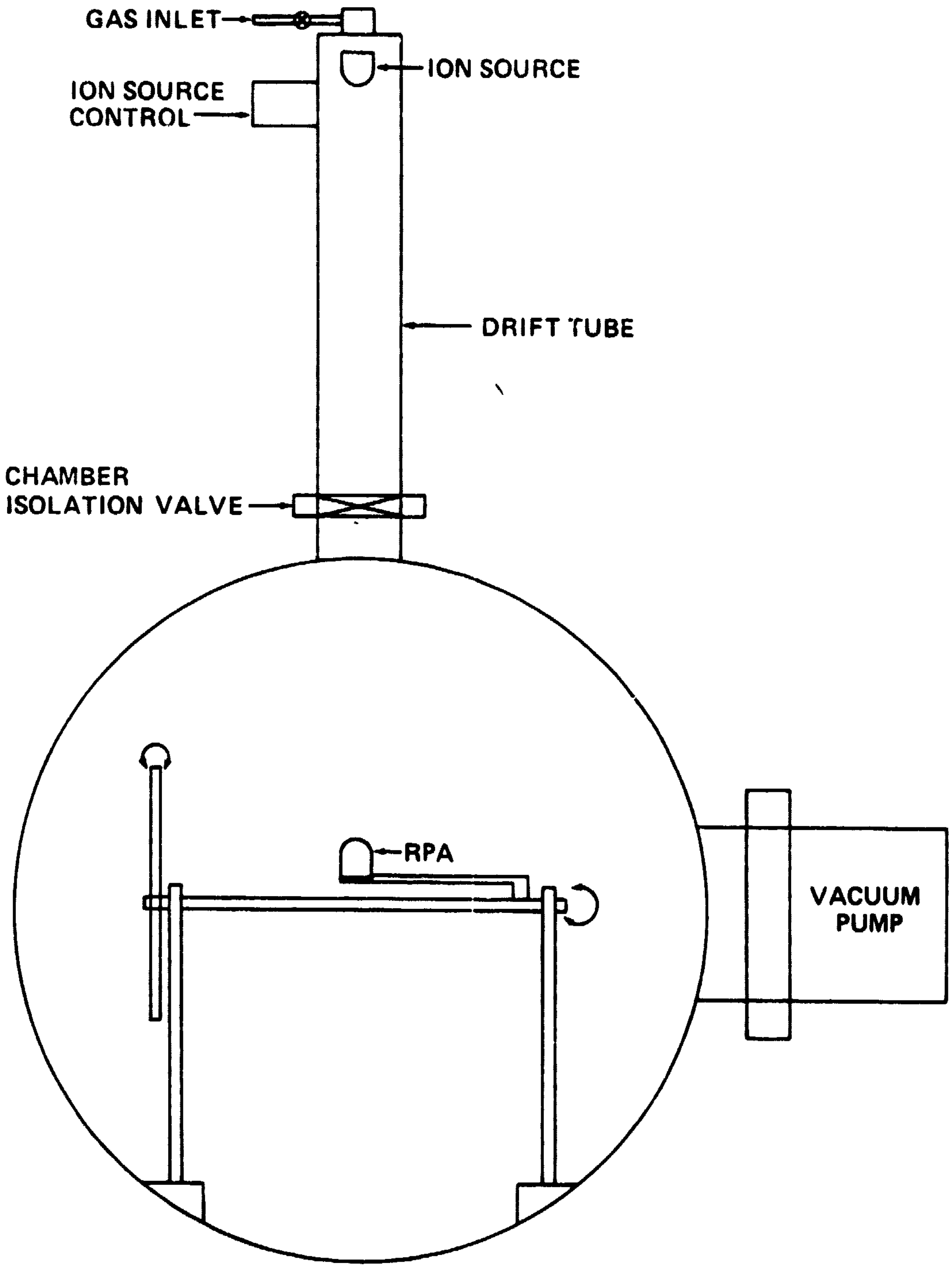

Figure 11. The ion source is located to provide a total drift path of 2.0 m to improve effective collimation. The chamber isolation valve prevents contamination of the source by atmosphere.

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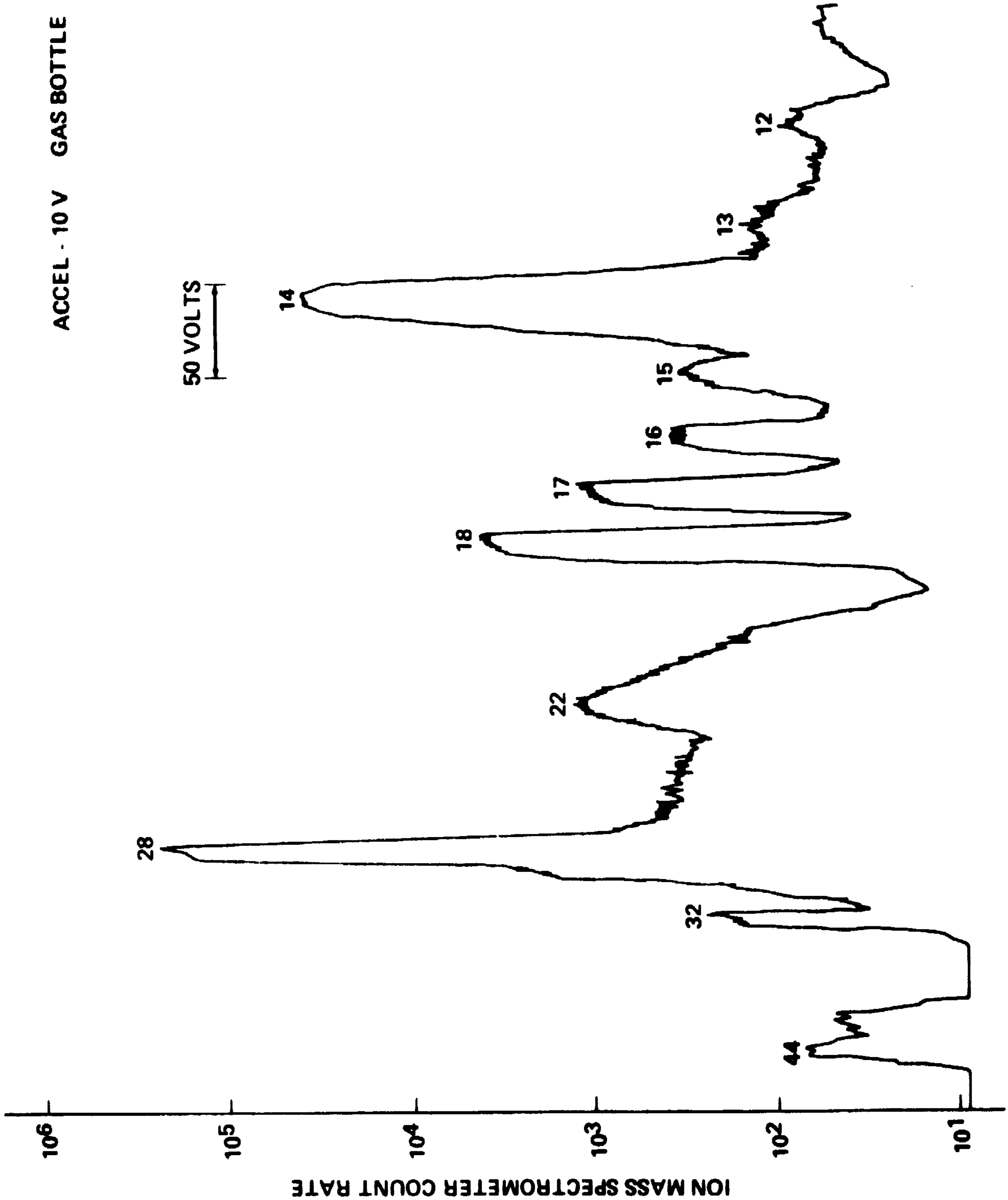

Figure 12. Ion Mass Spectrometer scan of source output at 10 eV using N_2 working gas.

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APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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Director, Space Science Laboratory